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THE MEASUREMENT OF LARGE VALUES OF AIRBORNE SOUND INSULATION

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INTRODUCTION

An important part of the specification of some of the areas used for broadcasting is their isolation from acoustic noise in an adjacent area. This is especially true for studios and control rooms in which programmes are being made or monitored. Appropriate criteria for the airborne component of the isolation have been derived for use within the BBC [1].

The airborne sound insulation criterion having been specified and a form of construction chosen which is intended to meet that criterion, the final result must be tested to confirm that it is satisfactory and meets the specification. To measure the degree of sound insulation provided between two areas it is the common practice to generate a sound field on one side of the partition and measure the transmitted components on the other side. The arithmetical difference in decibels between the sound pressure levels in the two areas is known as the Sound Level Difference (SLD). It is dependent on the sizes and acoustic properties of the two areas and on the proportion of the partition between them which is common to both, as well as the materials and the construction of the partition. This method is widely used for the measurement of airborne sound insulation. For the purposes of specification and measurement in broadcasting, the standardised corrections for the effects of the acoustics of the two rooms and the area of the partition (which lead to a normalised value for the sound insulation, SRI) are not usually applied because it is the effective reduction in sound pressure level which is important. In addition, the two areas may not have any common dividing partition. Under these circumstances, the notion of SRI is meaningless but the SLD can still be measured, in principle.

The measurement of the SLD by the direct method requires that a sound field be established in the source area at a level sufficiently high to enable the transmitted components to be measured in the receiving area. The transmitted components must therefore exceed the continuous background noise level in the receiving area by a margin adequate for them to be resolved reliably. In practice, a minimum margin of 6 - 10dB is required, more if the background noise level is unsteady. In mechanically ventilated rooms, even with the very low overall noise levels that are the rule in studios, the level of noise at low-frequencies is relatively high. Even with only a modest amount of sound insulation, to exceed the low-frequency noise levels by a sufficient margin requires high sound pressure levels in the source area. At higher frequencies the ventilation noise level is less but it is the nature of the sound insulation of partitions to give more insulation at the higher frequencies. Thus, the measurement is no easier and, in practice is usually more difficult.

An example of the sound levels required is given by Figure 1 which shows (a) the receiving area background noise level, (b) the sound insulation specification and (c) the source area noise level required to make the measurement, with an assumed margin of 10 dB. This example is not extreme, it is in fact the specification for one ordinary 'talks' studio adjacent to another. The source sound pressure level required is high but is achievable using an easily portable loudspeaker. Figure 1(d) shows the maximum sound levels which can be produced in a small room using the loudspeaker, which was specially developed for this application.

In many situations much higher values of sound insulation are required and have to be measured, more than 40 dB higher in some cases. No practicable loudspeaker will produce sound fields of the intensity necessary and over the required range of frequencies using the continuous excitation method. For about 20 years it has been the practice, under such circumstances, to use small explosive charges as the sound source. Until recently the results obtained using these explosives have appeared to be satisfactory, despite a number of potential deficiencies.

IMPLICATIONS OF IMPULSIVE MEASUREMENT OF SOUND INSULATION

During experimental comparisons of continuous and impulsive methods of measuring sound insulation some significant differences were observed between the results obtained from the two methods. The classical definitions and theory of airborne sound insulation are based on steady-state sound fields. Using an explosive charge to generate an acoustic impulse and thereby measure sound insulation raises several questions:

1) Is the steady-state sound insulation, defined and usually measured on the basis of power flow with its implicit time dimension, the same as the time-function of the impulse in the source area convolved with the time-responses of the partition and the receiving room?
2) What is the response of the 'steady-state' measuring equipment to the time-functions of the sound pressure levels?
3) Close to the explosive charge, the initial shock-wave is very likely to be in a regime where the incremental change in air pressure is a significant fraction of the static atmospheric air pressure. At what distance from the charge can the acoustics be considered to be linear enough for practical purposes?

THEORETICAL CONSIDERATIONS

In the absence of non-linearity the theory of the Fourier Transform indicates that information contained in a system impulse response (in the time domain) is identically equivalent to that in the steady-state transfer function (in the frequency domain). The magnitude of the ratio of the two Fourier transforms, one of the source and the second of the received time functions is, therefore, the same as the SLD.

In principle, this theory would appear to answer the first of the questions posed above, on the fundamental validity of impulsive methods. Because of the question of non-linearity, the first line of investigation was the linearity of the present system at the sound pressure levels encountered using the explosive charges, and, by implication, the measurement of those levels.

RESPONSE OF PRESENT INSTRUMENTATION TO IMPULSIVE SIGNALS.

The measuring system presently used by the BBC is based on a real-time spectrum analyser. When used to measure sound insulation using explosive charges it is set to record the 'peak' rms value of sound pressure level in each frequency band. This is a very different method the Fourier Transform method, because it does not use the time functions of the two signals to derive the spectra.

In order to measure the relative responses of the measuring system, a comparison of steady-state and impulsive methods was carried out. It was inconvenient to do this using real explosions and partitions so an electrical analogue of a simplified, symmetrical cavity wall partition was devised and tested using electrical signals.

Measurements of the 'insulation' of this model partition were made using continuous, swept sinusoidal waveforms and a number of different shapes of simple electrical pulses with crest factors of about 20 dB. Care was taken to avoid any overload of the measuring system. The theoretical 1/3rd octave band response was also calculated. No significant differences were found between the impulsive, the steady-state and the theoretical results, despite the use of crest factors somewhat larger than the specified maximum.

A possible explanation of the anomalous results sometimes obtained using explosive methods to measure sound insulation is that some part of the signal processing chain was overloaded. The effects of such an overload would be dependent on which part of the system was overloaded and its response to that overload. Two sets of measurements were made using the electrical model and deliberately causing an overload of the spectrum analyser circuits. For the first set of measurements the input signal to the model was made to overload the spectrum analyser. The second set of measurements was made, on the same electrical model, causing the spectrum analyser to overload on the output waveform. The results showed that allowing the measurement system to overload on either the input or the output signal causes errors in the measured insulation. With simple waveforms such as the test input signals, the errors were regular. However, with more complex waveforms the errors were also complex. In the case of a 16 dB output overload, the regular appearance of the theoretical isolation characteristic had largely disappeared from the measured results. In real acoustic measurements using impulsive methods, both the input and the output signals will be complex in shape and liable to give equally large errors if overload of the measuring equipment were to be permitted.

It may seem a trivial and self-evident point that instrumentation should not be overloaded but, in the field of acoustics, it is not always easy to determine whether or not overload is likely.

AIR NON-LINEARITIES

The pressure and the volume of a given mass of air are related by a reciprocal law. However, all of conventional room acoustic theory assumes a linear incremental relationship. Even loud normal sounds, for example, close to a jet aircraft at take-off, have dynamic sound pressure levels about 1000 times smaller than the static air pressure. The linear simplification is therefore justified in most cases. It is obtained by taking the first term only of a series expansion. The derivation of the propagation properties of acoustic energy, taking into account additional terms, shows that the harmonic content increases as a function of distance in the direction of propagation.

In a conservative system, this can only mean that energy, initially at low frequencies, is converted to energy at higher frequencies. Thus, a measurement of sound pressure level in the non-linear region will lead to over-estimation of the low frequency energy and under-estimation of the high frequency energy of the wave after it has propagated an additional distance. The magnitude of this effect is such that, at 600 Hz a plane wave, initially undistorted and of amplitude 150 dB re 20 μPa, has been measured as having a second harmonic component equal to 10% after a distance of 400 mm. In practice, such plane-wave propagation is not encountered in the vicinity of a small sound source. Because the amplitude of a spherical wave reduces by 6 dB for each doubling of distance the harmonic content will remain essentially constant beyond a certain radius. Nevertheless, at close range and with very loud sources this effect is significant and may influence the results obtained from sound insulation measurements. However, with an impulsive sound that contains all frequency components simultaneously the effect may not be separately distinguishable. It will be seen later that measurements of the sound generated by an explosion showed no significant spectral changes after a doubling of the propagation distance, from 6 m to 12 m.

It might seem somewhat far-fetched to discuss such levels of sound in the context of broadcasting studios but it will be seen later that the explosive charges often used to carry out these measurements are capable of generating sound pressure levels greater than 1/10th of the static air pressure at a distance of 1 m. At these levels, the propagation is unquestionably non-linear.

SOUND LEVELS PRODUCED BY THE EXPLOSIVE CHARGES

To establish the sound pressure levels produced by the explosive charges a measurement was arranged in a 'free field'. Because it was suspected that very high sound pressure levels would be involved it was necessary to remove the measuring microphones to reasonable distances. The measurement was carried out in the open air at a height of about 12 m. Two 6 mm precision microphones were set up at the same horizontal level as and at distances of 6 and 12 m from the explosive. The microphones had inherent overload levels of 174 dB re 20 µPa and sensitivities of 2 mV/Pa. No voltage gain was used in the microphone buffer amplifiers which had a specified voltage overload of greater than 5 V peak. The electrical limit of measurable sound pressure level was therefore about 162 dB re 20 µPa.

Figure 2 shows the time function of sound pressure level recorded from the microphones at 6 m and 12 m. The peak sound pressure level at 6 m was close to 160 dB re 20 µPa. The level at double the distance was 6 dB lower. These are very high peak sound pressure levels. They are likely to cause instantaneous hearing damage to an unprotected observer. Measurements of sound insulation previously carried out using these explosive charges have not taken into account the amplitude of the initial shock-wave; none of the types of microphones used in the past for this type of measurement are capable of measuring such levels without very significant overloading taking place. Also, the electrical measuring equipment normally used does not have the dynamic range necessary to record such high crest factors satisfactorily.

It is interesting to speculate how meaningful measurements of sound insulation have ever been obtained using such explosive charges. There are at least two reasons why the results might not be as bad as have been indicated so far. Firstly, some of the rooms in which sound insulation has been measured have been very large, allowing greater distances between explosive and microphone. The second and probably the most significant factor is that, when a charge is detonated all of the energy is initially contained in a thin, spherical shell consisisting of a rapid increase in pressure followed by a less clearly defined, negative-pressure recovery zone. The sharper the explosion the better defined is the initial shock-wave. Figure 2 shows that these types of charges have a very clearly defined shock front, of the order of 40 µs total duration. This is equivalent to a propagation distance of about 13 mm. All of the explosive's acoustic energy is contained in the transient shell which is about 4.5 ms duration at 6 m, and most of it within the initial shock front. After some time in a room, parts of this shell will impinge on a solid surface and will be reflected in some other direction. After a little more time, even in a large room, the sound field will be diffuse. By that time, all of the acoustic energy which has not yet been absorbed by acoustic treatment will be distributed evenly throughout the volume of the room and will gradually decay according to the reverberation characteristic for the room. The ratio between the volumes of the transient shell at, say, 6m (5.9 m^3) and the whole room (say 100 - 10000 m^3) shows that the sound pressure level quickly falls to reasonable levels. This process will not take long even in a large room; for example Manchester Studio 7, with a volume of 8200 m^3, has a mean free path of only 38 ms. If the recovery from overload is fast enough to record the lower level but longer duration decay period as the effective sound pressure level then the measurement will be satisfactory, provided that the equipment applies the same time-weighting function on the receiving side of the partition.

Figure 3 shows the spectra of the explosion, recorded at 6 m and at 12 m. It shows that there is no significant difference, apart from that of 6 dB in level, as a result of the additional propagation distance. Fig. 3 also shows that the spectrum contains more energy at low-frequencies than at high-frequencies. It has a peak at about 250 Hz, corresponding approximately to the reciprocal of the total duration but is about 20 dB down at 2 kHz. This is not an ideal spectrum for the measurement of sound insulation which invariably has generally larger values at high frequencies than at low.

ASSESSMENT OF PRESENT METHODS

It seems from the foregoing that the use of impulsive methods of measuring high values of sound insulation involving the use of explosives has been fortuitous in giving apparently meaningful results. The magnitude of the initial shock-wave from the explosion is sufficient to cause overload of any of the types of microphones used for this work. However, all of the measurement chain has apparently usually recovered sufficiently quickly to make a reasonable assessment of the longer-lived but lower sound pressure levels which remain after diffuse sound conditions have been established in the room. It is also surprising that the equipment's response on the receiving side of the partition has been sufficiently similar, despite the lower peak sound pressure levels and the radically different spectral and temporal distributions, to give apparently valid difference results. It is even more surprising that over a period of about 20 years and several different generations of measuring equipment the results have appeared to be credible.

However, this present work has shown that the method is unreliable unless care is taken to avoid equipment overload. By using less sensitive microphones and lower gain settings, especially on the source side of the partition, linearity of the equipment can be assured. However, whether there would then be sufficient dynamic range remaining to measure the main part of the excitation signal is questionable.

AN ALTERNATIVE METHOD

An alternative method which can be applied in those cases where high values are being measured uses averaging in the time domain to improve the receive-side signal-to-noise ratio. Instead of obtaining the total signal energy required for the measurement from a large signal, this method extends the measurement period to obtain the same result. In principle, the measurement signal is integrated synchronously whilst the uncorrelated extraneous noise integrates towards zero. Each doubling of the number of measurements results in 3 dB improvement. With stable excitation signal, propagation path and synchronisation, there is no theoretical limit to the amount of improvement which can be obtained in this way. Thus, a measurement of sound insulation can be made when the receive-side signal is far below the continuous, but uncorrelated, noise level. This method reduces the requirement for source-side sound pressure levels, thus making the existing equipment adequate. It would even be possible, in principle, to make a measurement subliminally whilst the rooms were being used for other purposes. It also has the advantage of being able to use an apparently random, noise-like signal which, if it were audible, would be less obtrusive to other users of the building.

However, there are some additional practical limitations. Firstly, the requirements of the signal are that it should have an adequate bandwidth for the measurement, it should be of a type in which all frequency components are present at all times and it must be deterministic because each measurement must be an exact repeat of the previous one. It should also, ideally, have a low peak-to-mean energy ratio in order to maximise the signal energy within the limitations of the loudspeaker and the analysis equipment. There are also constraints on the duration and the repetition rate of the excitation signal. Obviously, it must last long enough to 'fill' the input store of the analyser. It is not so obvious that the repetition period must be long enough to allow the preceding signal to have decayed into insignificance, otherwise some long delayed but perhaps partially coherent remains of the previous measurement period might be included in the integration. A filtered, pseudo-random sequence, generated by a maximal-length, binary feedback shift-register satisfies most of these conditions.

The dynamic range of the instrument used to integrate and analyse the signals is also important. It must be capable of reading, storing and ultimately averaging to near zero, without distortion, the continuous, unwanted random background noise. At the same time, it must have sufficient resolution to represent the wanted signal to a reasonable degree of accuracy. Modern digital instrumentation capable of carrying out the necessary functions of storage, integration and analysis typically has 14 or 16 bit input resolution giving dynamic ranges of 80 - 90 dB. With 30 - 40 dB to represent the signal and 10 dB to allow for the range of the unwanted noise, this leaves only 30 - 50 dB for signal-to-noise ratio improvement. Specialised analysis equipment which did not truncate the averaged data would not suffer from this limitation but is not currently available.

There is also a practical limitation on the time for which these measurements can be carried out. Because of the need to double the number of samples for each 3 dB improvement in signal-to-noise ratio, the time taken for large improvements can become great. For example, in the case of a drama studio with a reverberation time of 0.5 s the repetition period could not be shorter than about 0.25 s. To obtain a 21 dB improvement in signal-to-noise ratio requires 2^7measurements (a minimum of 32 s), which is not an unreasonable time. However, to obtain a 42 dB improvement would take a minimum of about 1 hour for each pair of microphone positions. Clearly, for routine measurements, this represents a practicable upper limit of the technique.

A test of this alternative method of measuring sound insulation was carried out on the same partition as used for the measurements described in Section 2. The instrumentation consisted of a pseudo-random noise source and a digital Fast Fourier Transform (FFT) Analyser which could be set to average, in the time domain, 1024 samples of a time-function in each of two channels. After the acquisition of the average data, the analyser transformed both signals to the frequency domain, converted them to 1/3rd octave analysis and displayed the difference. This was repeated at the usual several microphone positions and the sound pressure level results averaged, also in the usual way. The results obtained in this way for the averaged SLD showed no significant difference compared with those obtained using quasi-continuous sinusoidal excitation.

It is of interest to look at the actual signal levels involved in this measurement. Fig 4 shows three spectra; (a) is the continuous average noise level measured in the receiving room in the conventional way, as would be indicated on a normal sound level meter, (b) is the time-integrated spectrum measured without the signal source and (c) is the received signal after integration. It shows that the theoretical 30 dB improvement has been achieved, except perhaps in the highest frequency octave. It also shows that the received signal is, mostly, significantly below the continuous average noise level (by about 10 dB), and also, mostly, well above the measurement threshold. It can be concluded that, for this measurement at least, the excitation signal spectrum is not far from optimum.

CONCLUSIONS

One method for the measurement of high values of sound insulation using explosive charges has been studied in detail. In the past, the results from such measurements have caused some concern that the method might not always give the correct answer. Despite the philosophical and theoretical doubts about the method, it has been shown that it should give the correct result in principle, but that practical difficulties lead to the introduction of error-generating mechanisms. The peak sound pressure level generated by the explosive charge has been measured as 160 dB re 20 μPa at 6 m. This level is quite sufficient to overload any of the types of microphone used for such measurements, even if overload of the electronics in the measuring equipment is avoided. It seems that this overload and the subsequent recovery from it by the measuring system has been responsible for the errors. To avoid the overload would require the use of low-sensitivity microphones and low gain settings in the electronics. However, it is unlikely that there would then be sufficient dynamic range remaining to measure the majority of the signal energy, which is at a much lower level than the peak. This is a problem with any kind of impulsive measurement method which, intrinsically, contains all of the measurement energy in a short period of time.

The studies of the correction terms for the non-linearity in the propagation of sound in air at high levels have shown that, in principle, the generation of harmonics by the non-linearities ought to be significant. However, with a pressure pulse which contains many frequency components anyway, this effect is not noticeable.

An alternative measurement method has been described which does not require the use of such high sound pressure levels but uses integration in the time domain to extract the wanted signal. However, it may take several hours to improve the signal-to-noise ratio of a measurement by 40 dB, but the equipment may be left unattended and the random-noise-like test signal, if it were to be loud enough to be audible to other users of the building, would not be so objectional. Because of this time factor and some other practical limitations on the maximum improvement which can be made, it is unlikely that the method would usually employ lower signal levels than are presently used with the sinusoidal excitation method, but, for the same sound level, the method can be used to cover all the cases presently defined in Reference 1.

REFERENCE

[1] WALKER, R. 1981 Revision of the sound insulation requirements in broadcasting studio centres. BBC Research Department Report No. 1981/1.

ACKNOWLEDGEMENT

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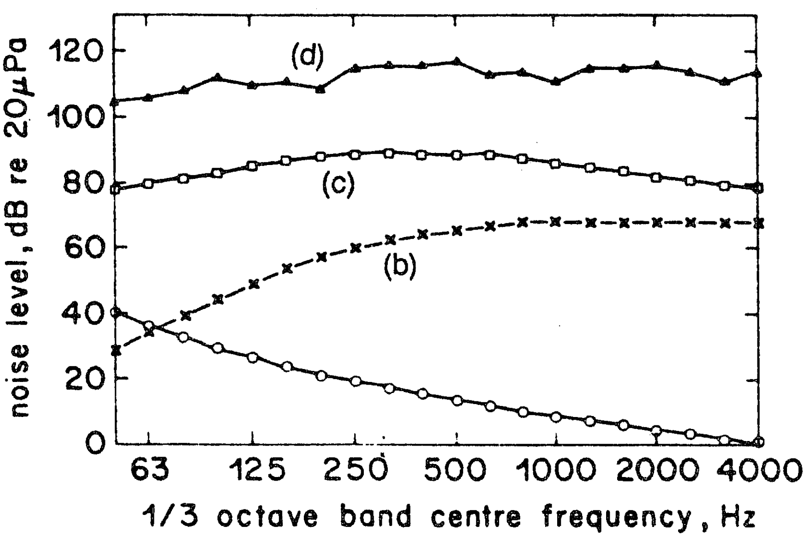

Figure 1.

Sound pressure levels for the continuous excitation method

(a) Background noise level
(b) Insulation criterion
(c) Minimum sound level for measurement
(d) Maximum loudspeaker output

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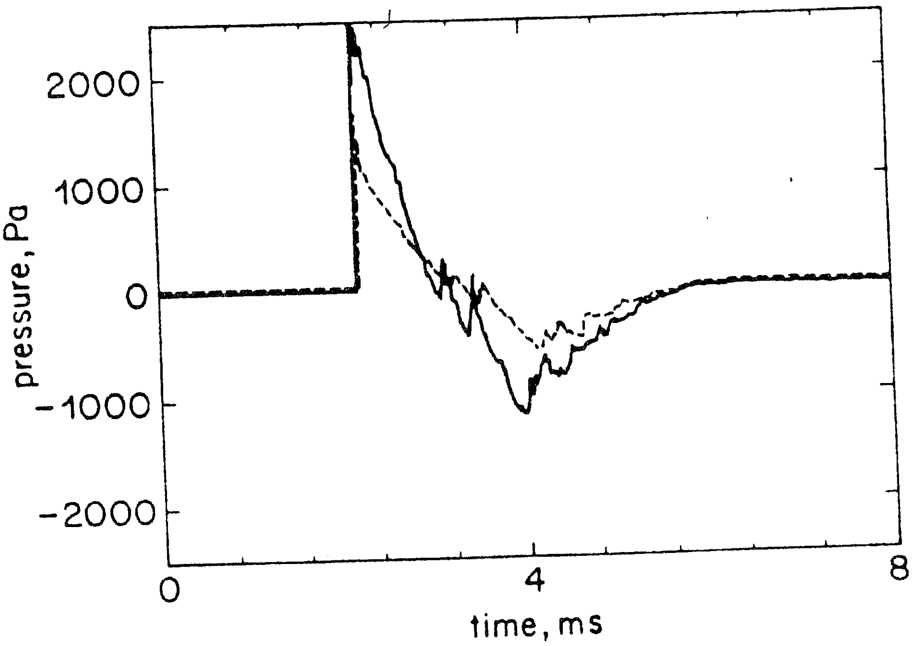

Figure 2.

Explosive impulse time functions at 6 m and 12 m

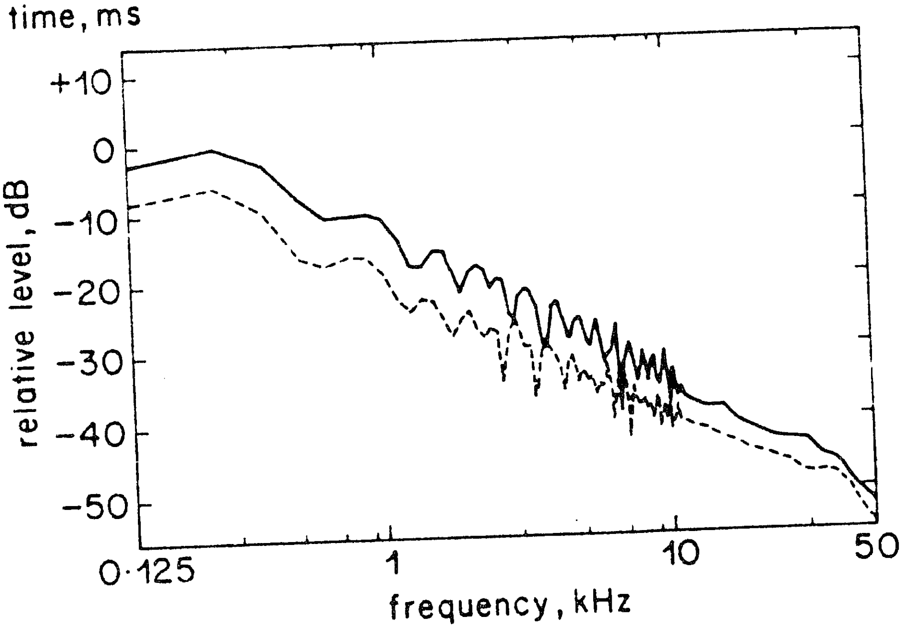

Figure 3.

Explosive impulse spectra at 6 m and 12 m

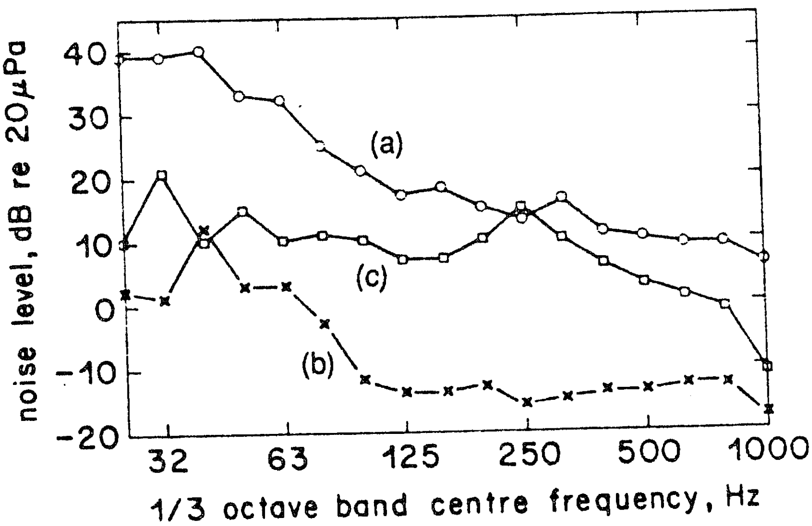

Figure 4.

Sound pressure levels for the time integration method

(a) Continuous noise level
(b) Integrated noise level
(c) Integrated signal level